Space-Time Adaptive Processing Using Sparse Arrays

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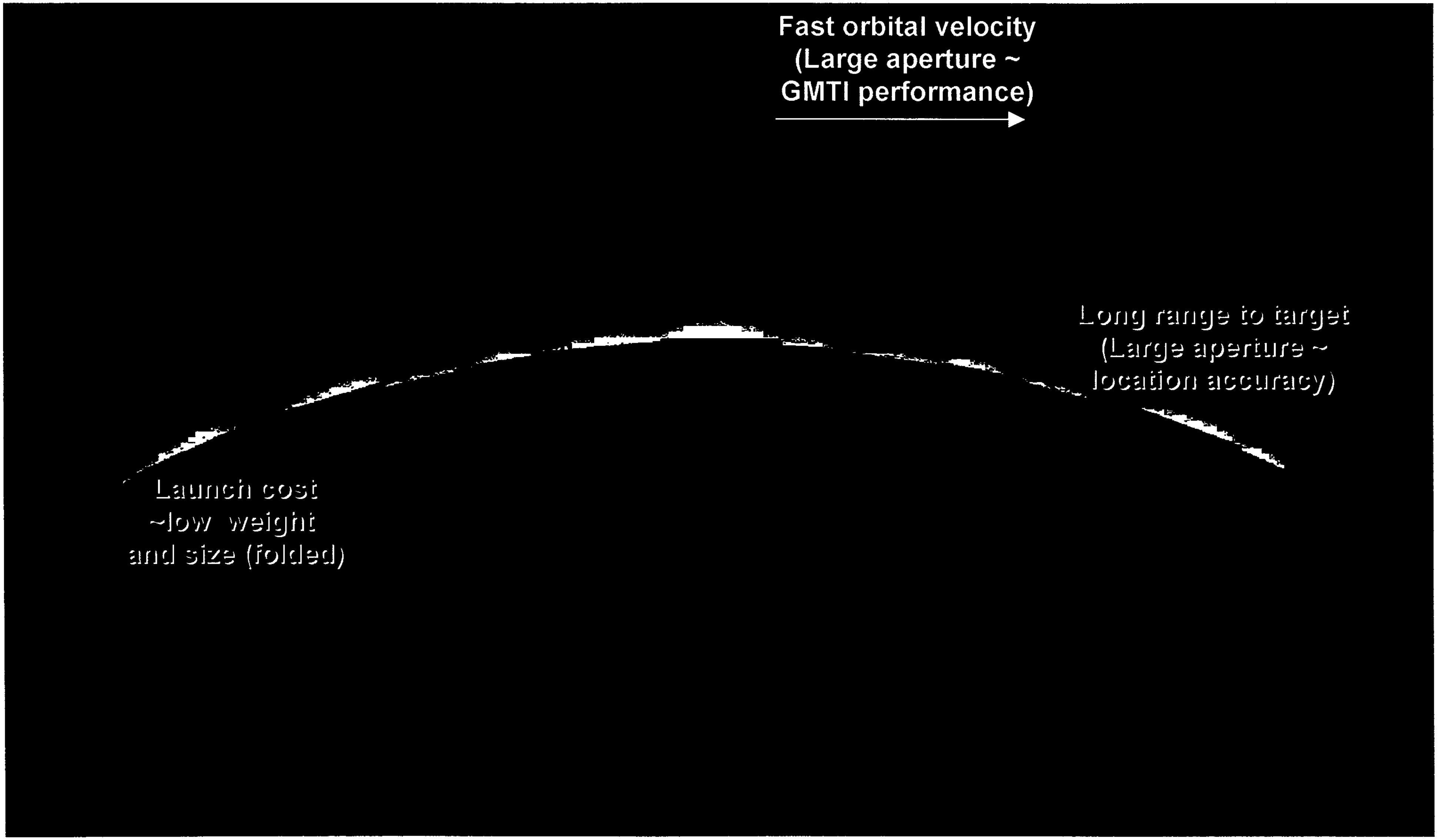
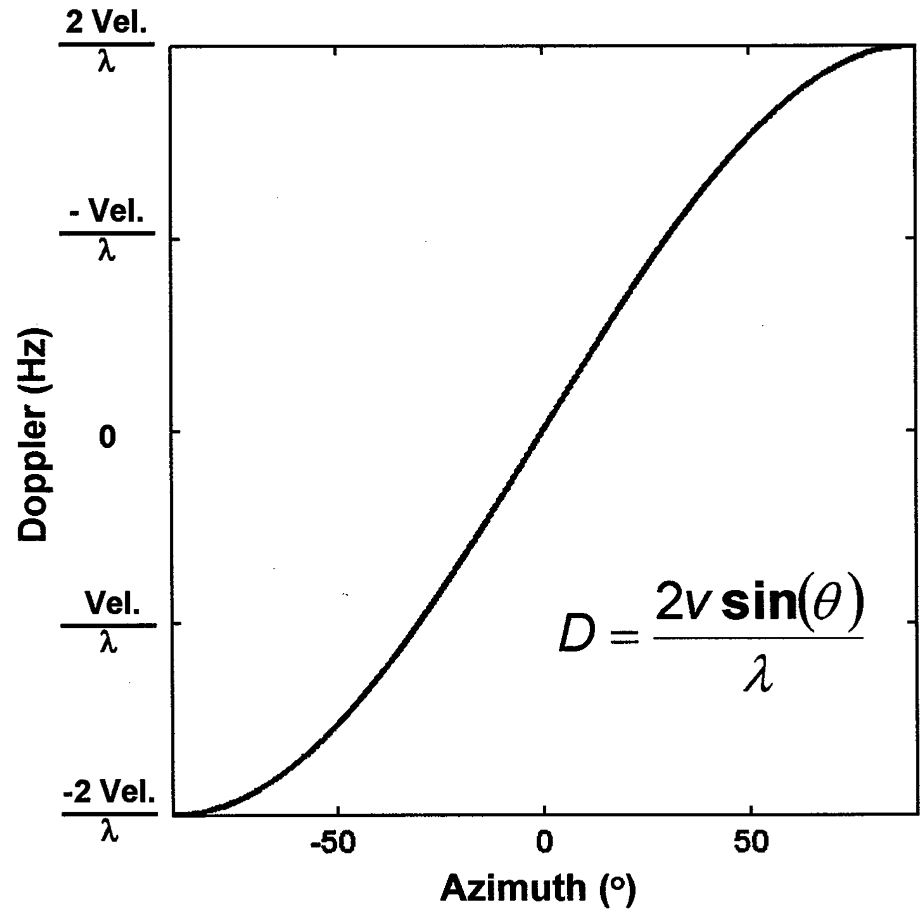
Application: Space Based Radar



Outline

- Introduction
- Theory
- Performance
- Summary

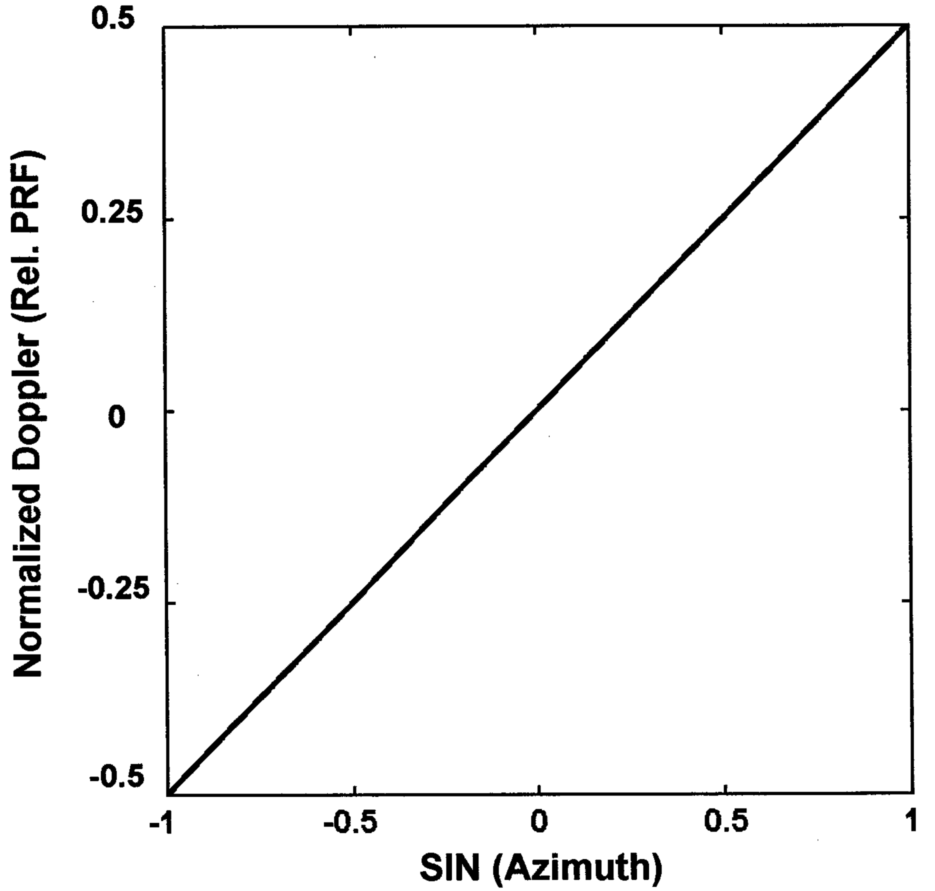
STAP Units



2 Vel. / λ
- Vel. / λ
0
Vel. / λ
-2 Vel. / λ
Doppler (Hz)
-50
0
50
Azimuth (°)
$D = \frac{2v\sin(\theta)}{\lambda}$

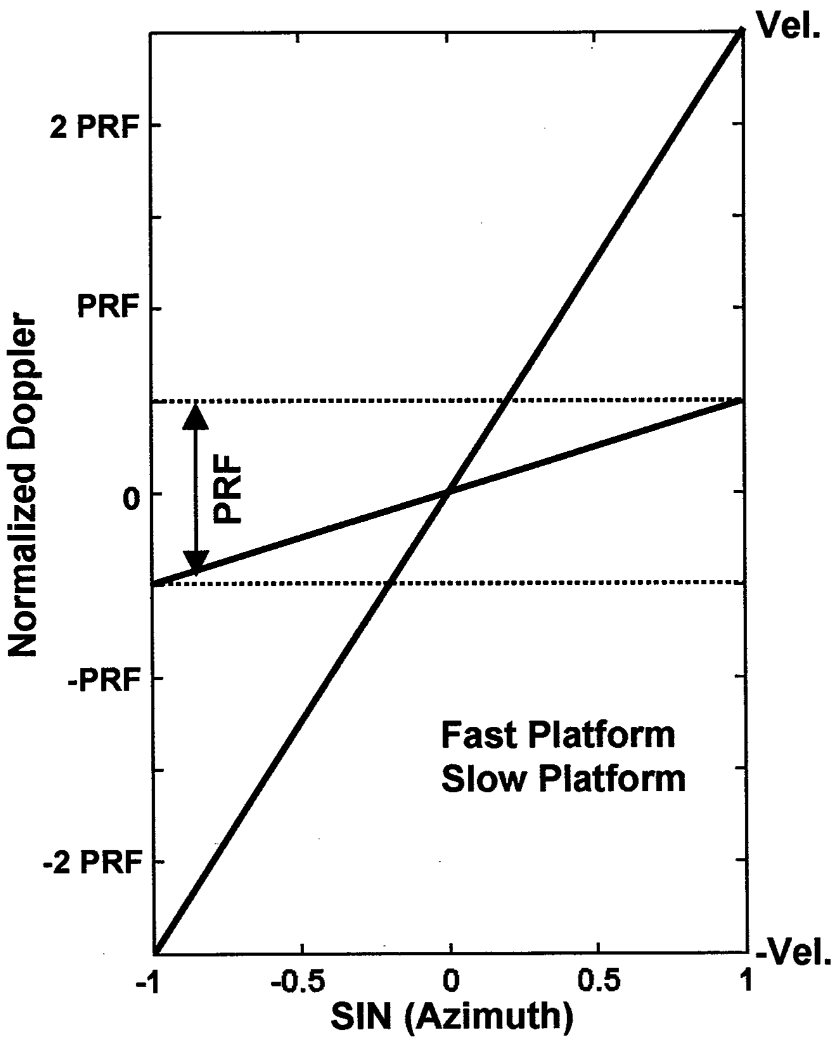
STAP Units

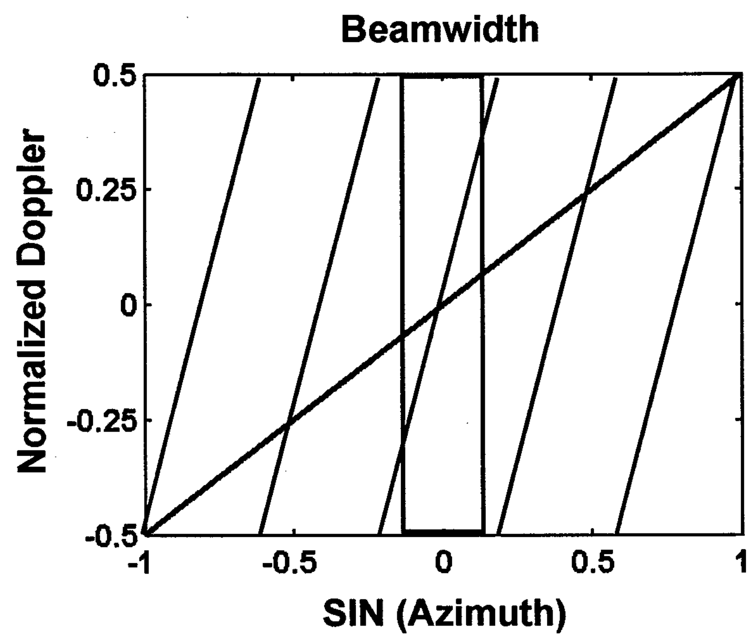
city



0.5
0.25
0
-0.25
-0.5
Normalized Doppler (Rel. PRF)
-1
-0.5
0
0.5
1
SIN (Azimuth)

Doppler Ambiguous Clutter

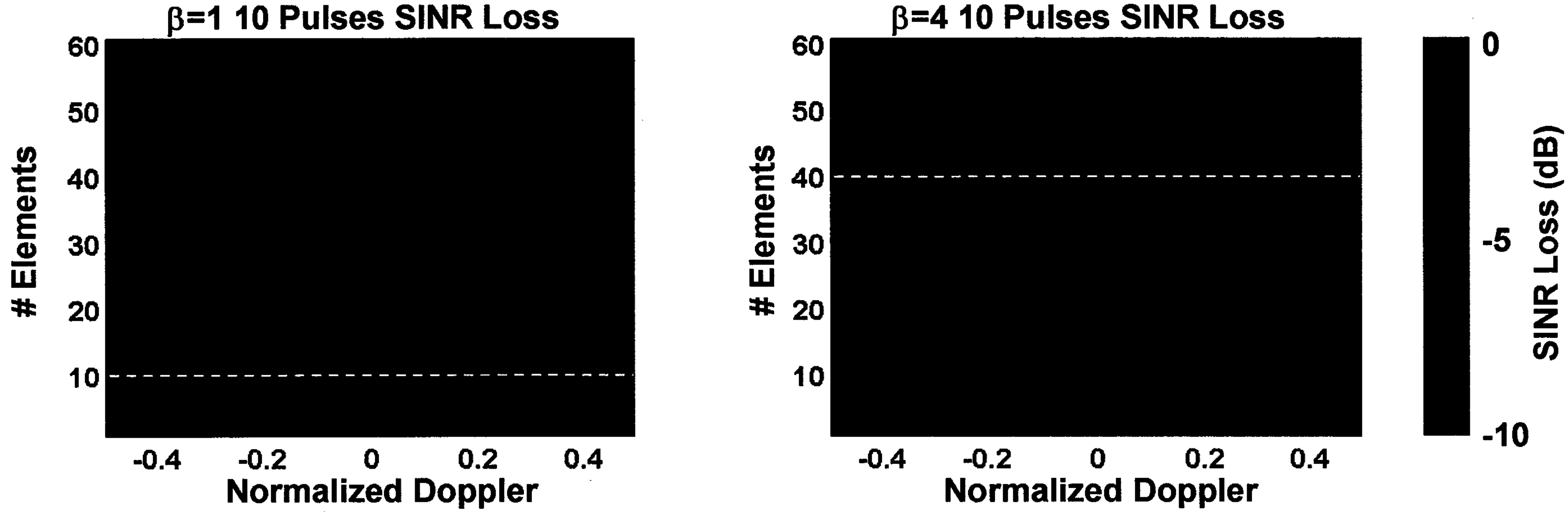




$$\beta = \frac{4v}{\lambda PRF}$$

$$\text{Main Beam Clutter Width} = \frac{\lambda 2v}{L}(\text{m/s}) = \frac{4v}{L}(\text{Hz})$$

Aperture and Doppler Limited Performance



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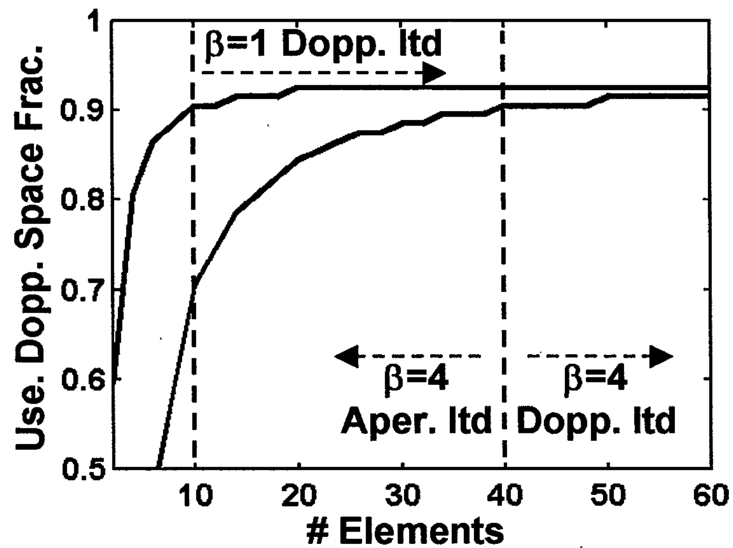
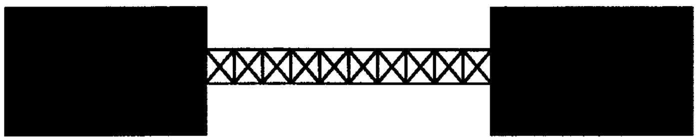
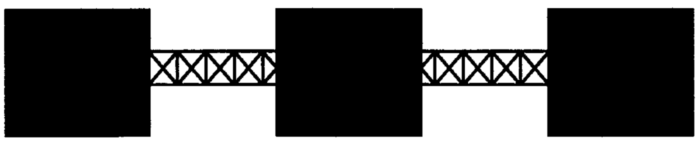


Some Sparse Array Concepts

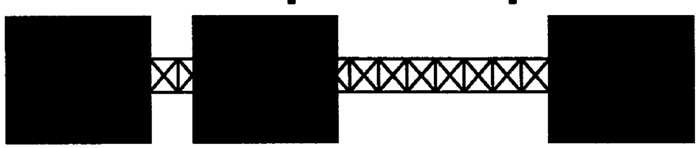
Interferometer



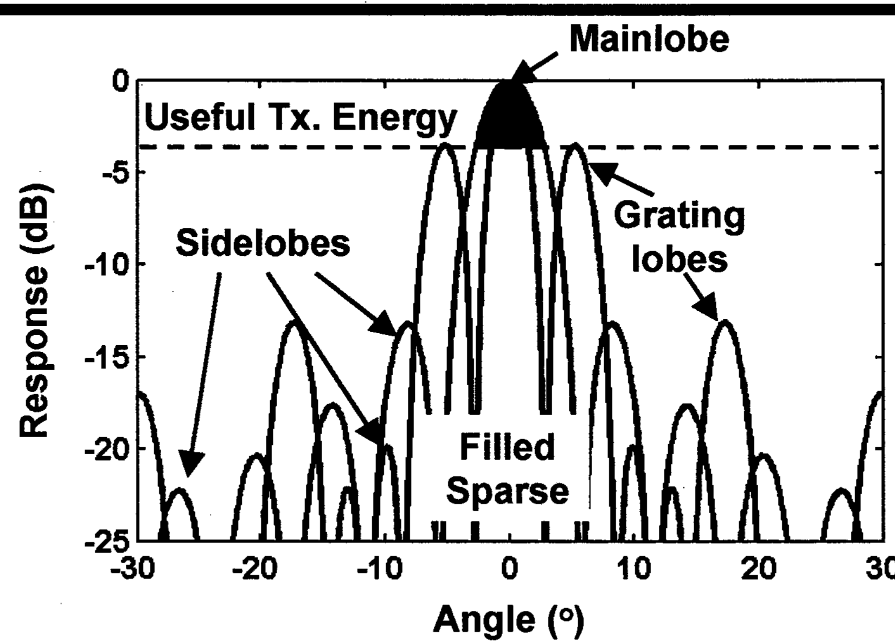
Even Spaced Equal Size



Uneven Spaced Equal Size



Many Apertures



- Sparse arrays trade mainlobe width against grating lobe height to find the optimum sparseness
- Energy transferred from the mainlobe to the grating lobes is useless for Tx.
  - Use a filled section of the sparse array for Tx. And form multiple Rx. beams

Sparse Array Issues

[redacted]

- Angle estimation performance
  - Improved accuracy due to narrower beamwidth (CRB)
  - Non-local errors due to grating lobes (WWB, ZZB, AB, …)
- SAR performance
  - Multiple spatial samples per pulse
  - Tight PRF constraints
- Hardware and cost
  - Sparse arrays require less hardware
  - Cheaper & lighter
- …

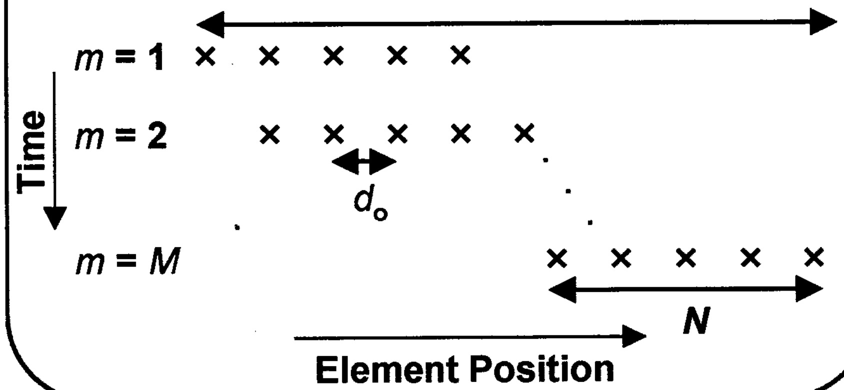
Outline

- Introduction
- Theory
  - Clutter Rank
  - Waveforms
  - SINR Loss
- Performance
- Summary

Brennan's Rule & Ward's Rules*

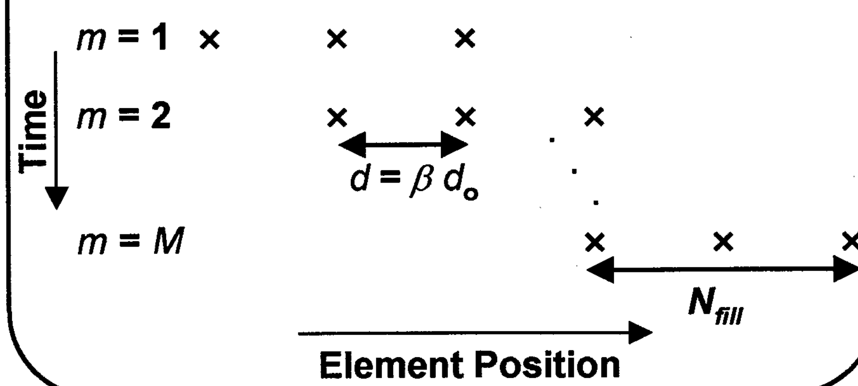
Brennan's Rule

Rank = Total Synthetic Aperture



Ward's Min Rank Rule

Min Rank = $N + M - 1$



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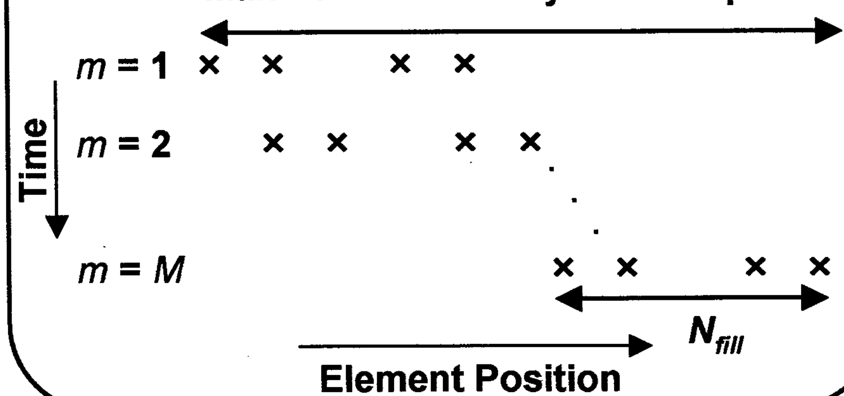
Ward's Max Rank Rule

Max Rank = Total Synthetic Aperture

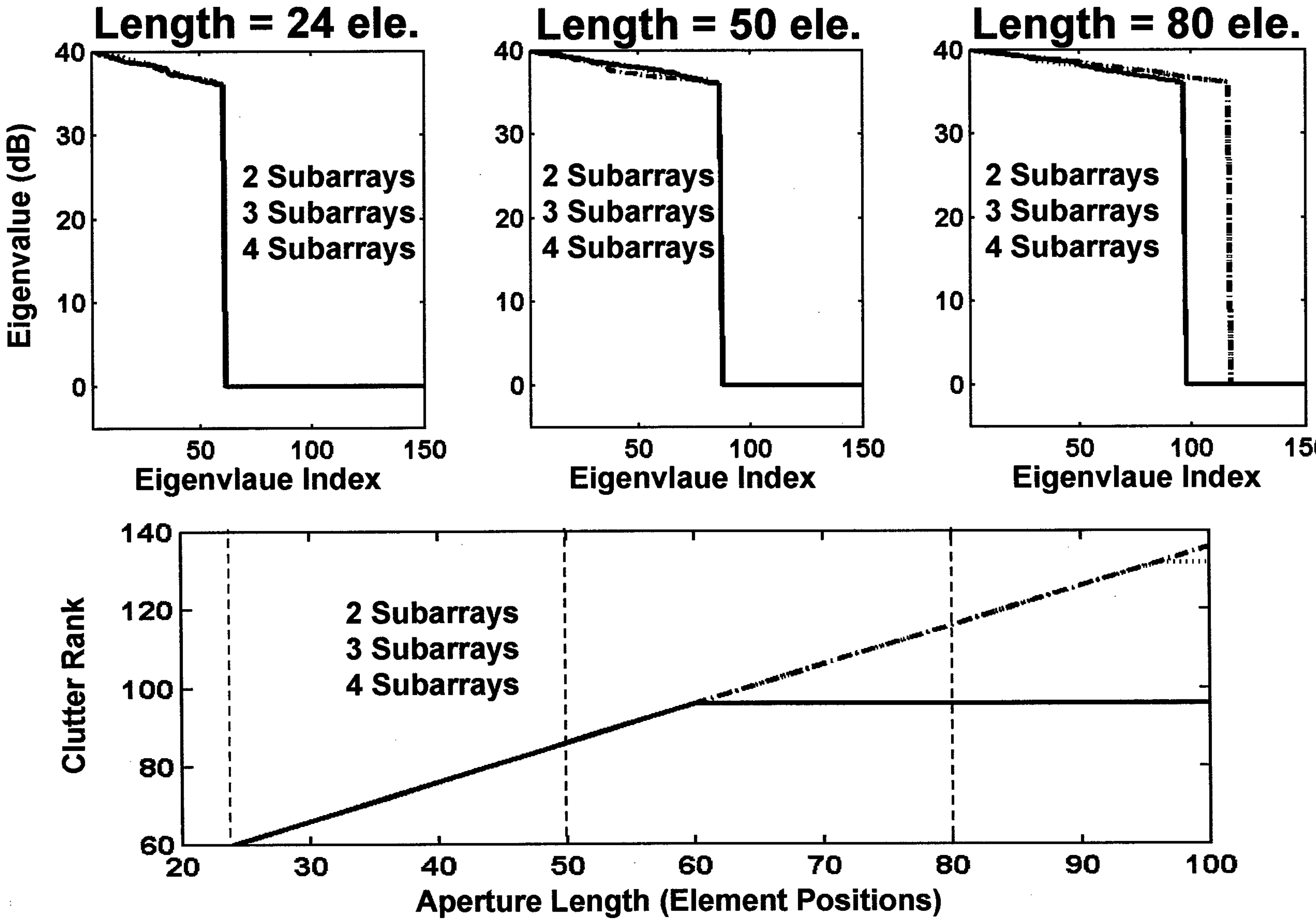


*J. Ward, Asilomar 1998

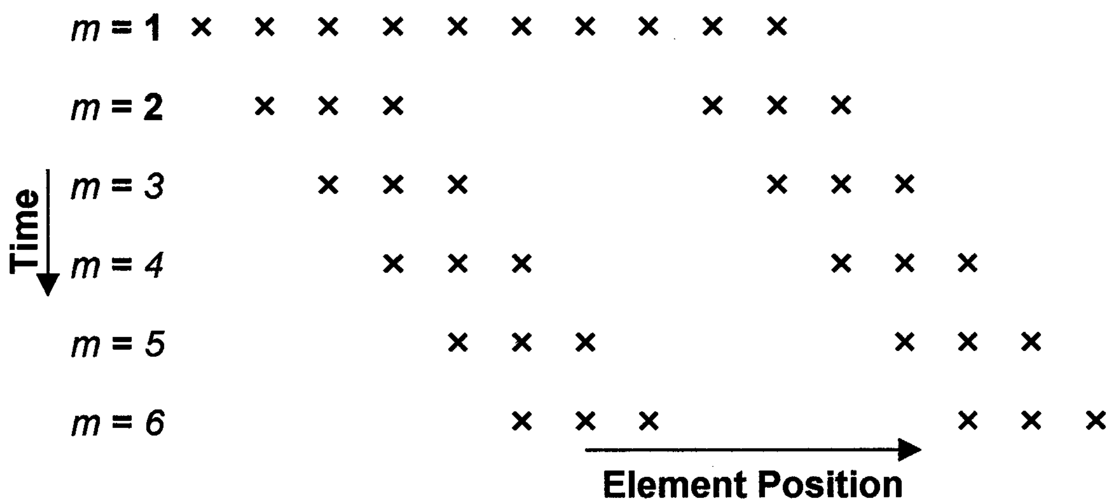
N = Number of elements, M = Number of pulses, $\beta = 2\, v\, T\, d_0^{-1}$, N_{fill} = Number of elements in filled array

Additional Sparse Array Behavior

$N = 24$, $M = 10$, $\beta = 4$ Example



New (?) Rules for Sparse Arrays



Rank=min[6+1+4,6+2*1]=min[11,8]=8

Rank=min[6+2+4,6+2*2]=min[12,10]=10

Rank=min[6+3+4,6+2*3]=min[13,12]=12

Rank=min[6+4+4,6+2*4]=min[14,14]=14

Rank=min[6+5+4,6+2*5]=min[15,16]=15

- **For arrays which move less than the smallest subarray aperture during a pulse the rank is given by :**

$$\min\Big[\underbrace{N+\beta(M-1)+G}_{\text{Jim Ward's } r_{max}}\ ,\ \underbrace{N+S\beta(M-1)}_{\text{Using each sub array independently}}\Big]$$

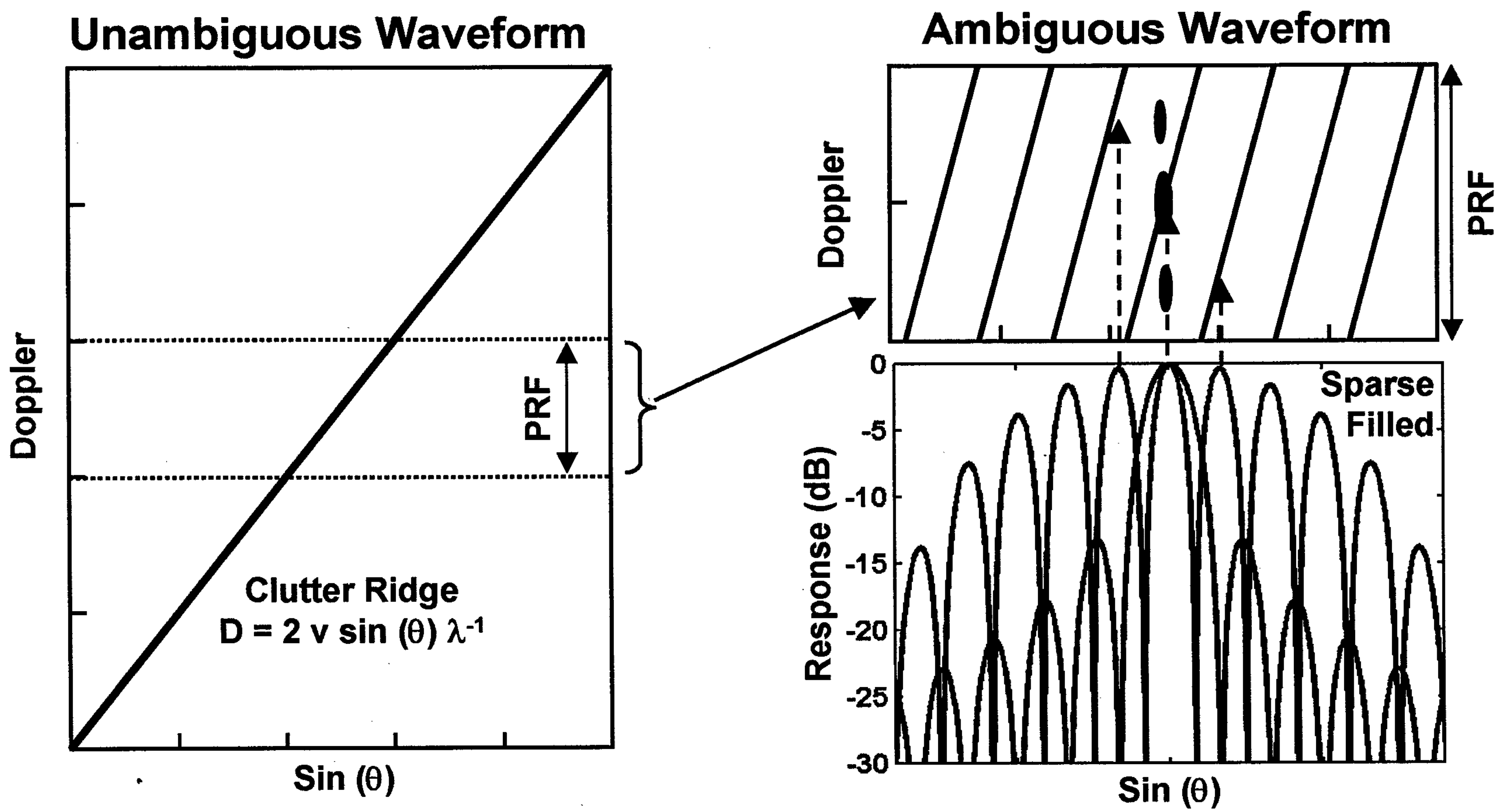
- **For equal size subarrays a sparse array is no better than a single subarray if**

$$G > \beta(S-1)(M-1)$$

- **I.e., The array is so sparse that there is no redundancy**

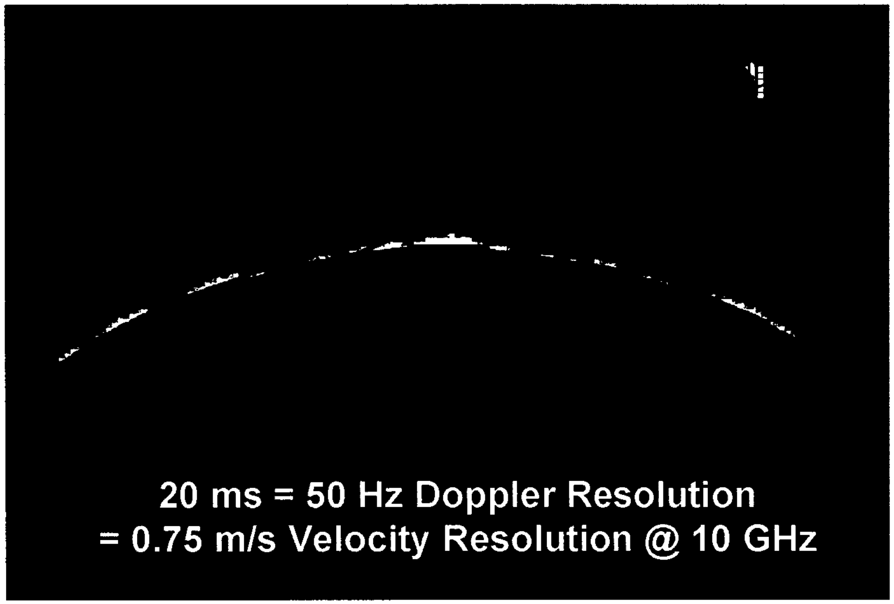
G = Sum gap sizes (element positions) S = Number of subarrays

Sparse Aperture Waveforms

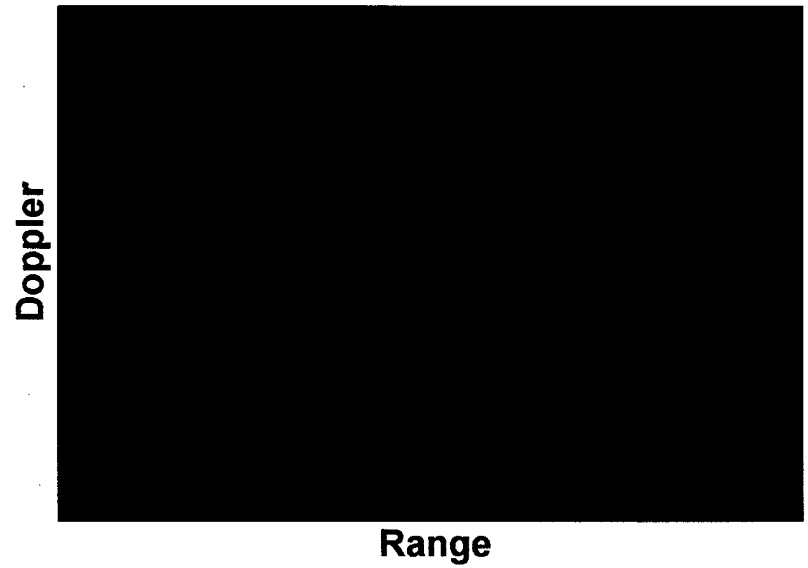


- Ambiguous waveforms (e.g., pulse-Doppler) and sparse (ambiguous) apertures lead to multiple clutter nulls
- Unambiguous waveforms preferable

Long Single Pulse Waveforms

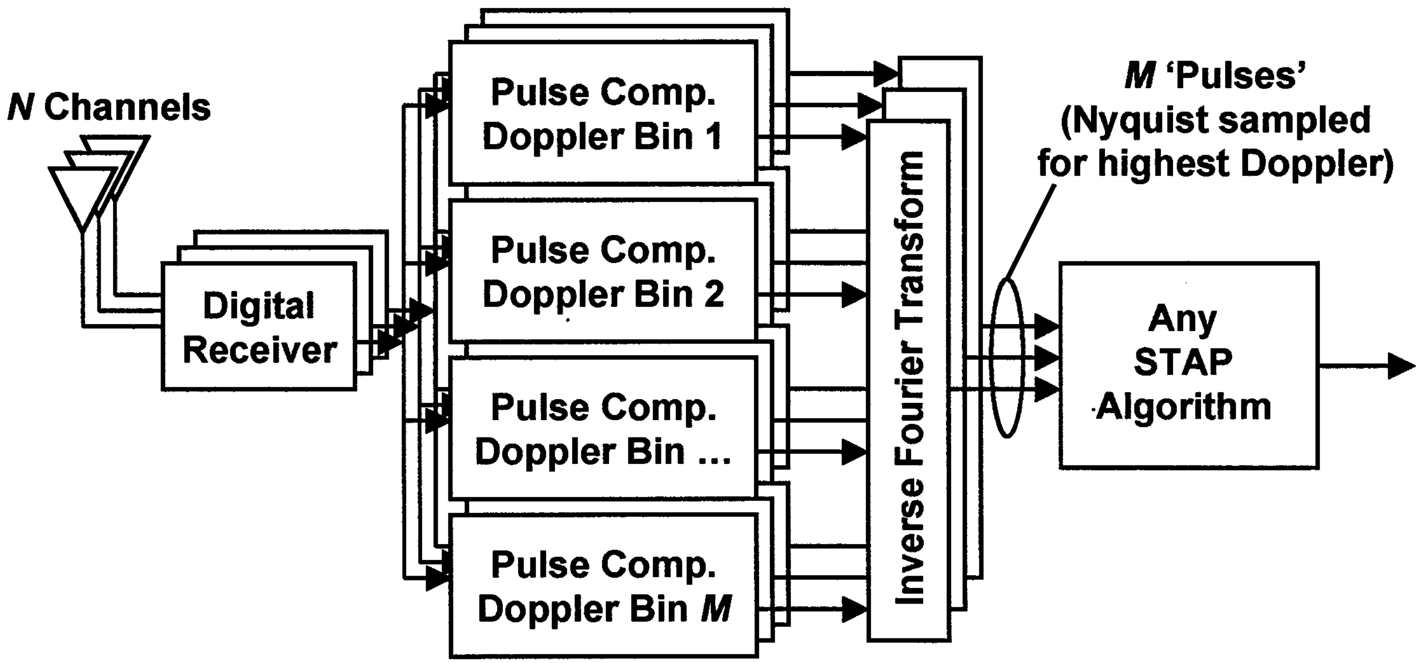


Phase Encoded Waveform



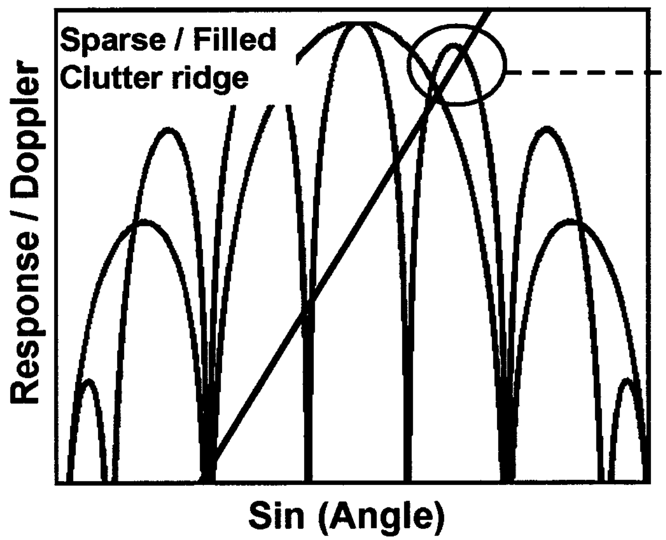
- Single pulse means no range or Doppler ambiguities
  - High chip rate sets Doppler ambiguities
- Must pulse compress each Doppler bin separately
  - More computation than pulse-Doppler waveforms
- Concern about strong sidelobe clutter > noise floor
  - Wide bandwidth & narrow antenna beampatterns

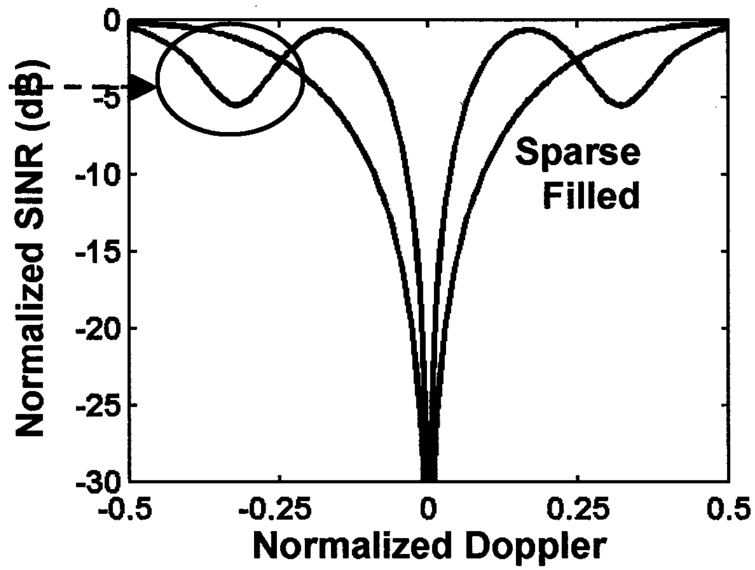
Processing Long Single Pulse Waveform



- Long single pulse radar can be made to 'appear' like a regular pulse-Doppler radar
- Looks like high PRF radar without the range ambiguities

Space Time Adaptive Processing





- **Grating lobes lead to reduced detection performance at particular Doppler frequencies**

$$\mathrm{SINR\,Loss} \approx \boldsymbol{v}^H \boldsymbol{v} - \left|\boldsymbol{v}^H \mathbf{e}\right|^2 = 1 - \frac{\mathrm{Grating\,Lobe\,Gain}}{\mathrm{Mainbeam\,Gain}}$$

- **Should not make the array too sparse**
  - **For <3 dB SINR loss grating lobe gain must be 3 dB less than main lobe gain (Σ grating lobes for pulse-Doppler waveforms?)**

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- Introduction
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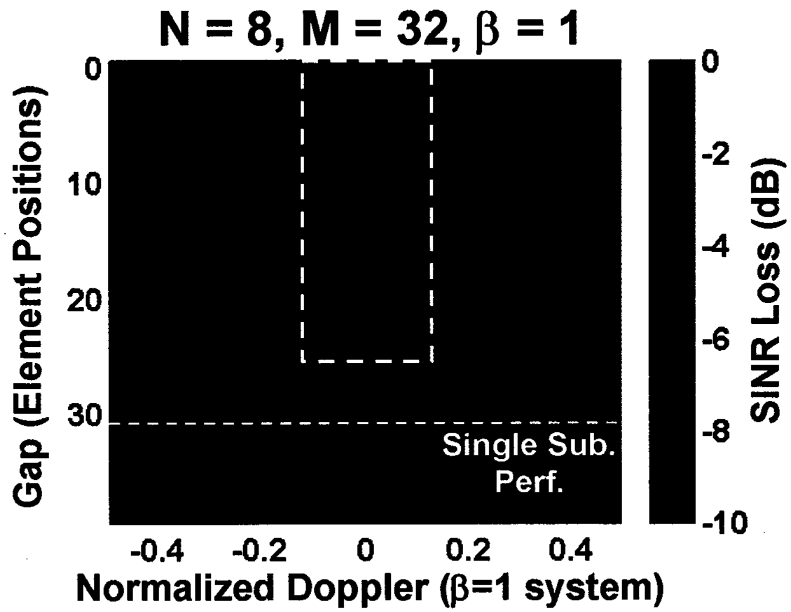
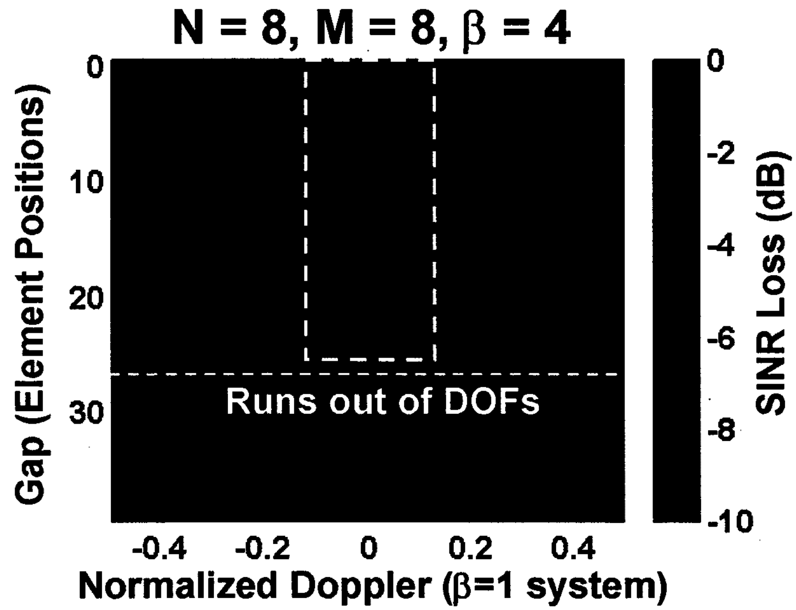
- Performance
  - Dependence on waveform
  - SBR Design Example
- Summary

Unambiguous vs. Ambiguous Waveforms
Interferometer Example



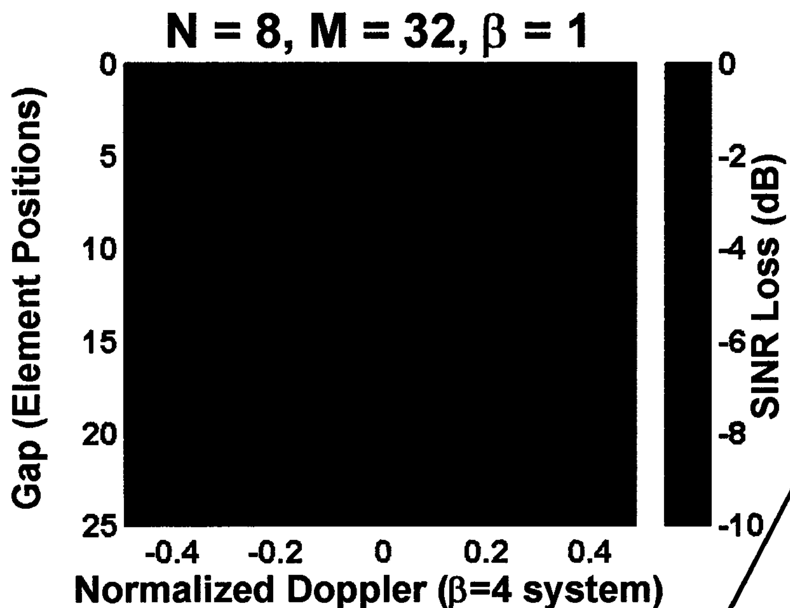


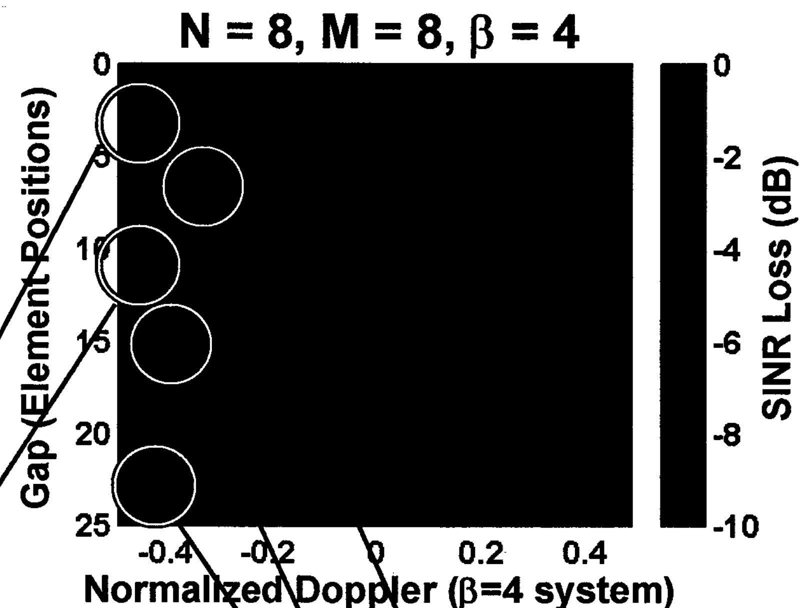
- Filled rank = 8+1(32-1) = 39
- Max. sparse rank = 8+2(32-1) = 70 (reached with a 31 element gap)

- Filled rank = 8+4(8-1) = 36
- Runs out of DOFs with a 27 element gap 8+27+2(32-1) = 63

[redacted]

Unambiguous vs. Ambiguous Waveforms





Grating lobes on Doppler ambiguous clutter

Multiple grating lobes on Doppler ambiguous clutter

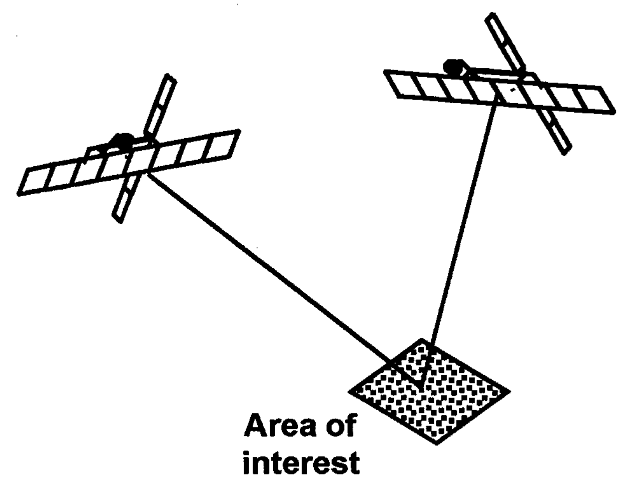
[redacted]

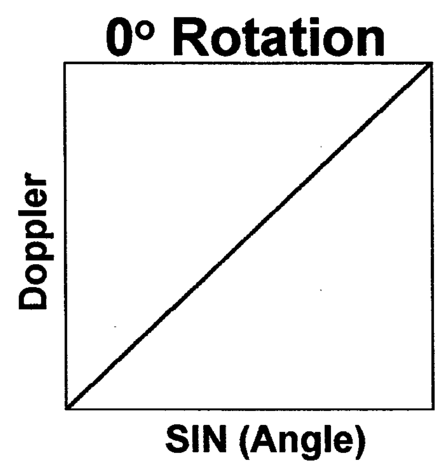
Space Based GMTI Radar Examples

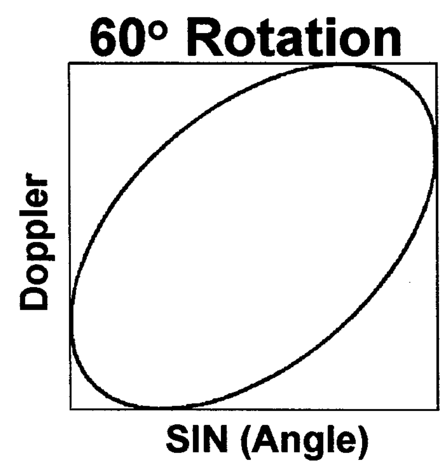
Parameters

- 32m x 2.5m filled aperture
- 10 GHz operating frequency
- 1000 km orbit
  - 7282 m/s orbital velocity
- 1 kw peak transmit power
- 200 MHz bandwidth
- Unambiguous waveform
- -12 dB const. γ clutter model
- 2500 km range
  - 16.67ms CPI length
  - Travel ~120m in a CPI

Scenarios

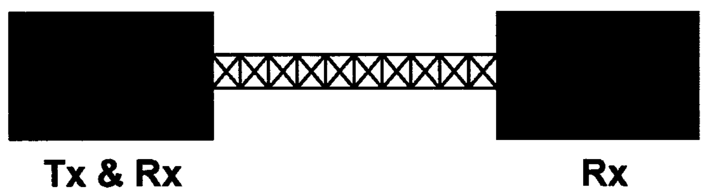




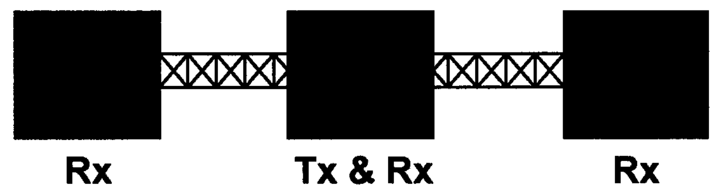


Space Based Radar GMTI Designs

Interferometer Array

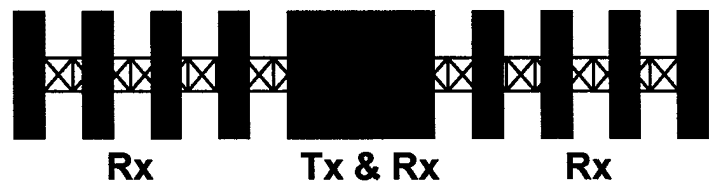


Even Spaced Equal Size



Uneven Spaced Equal Size

Many Apertures



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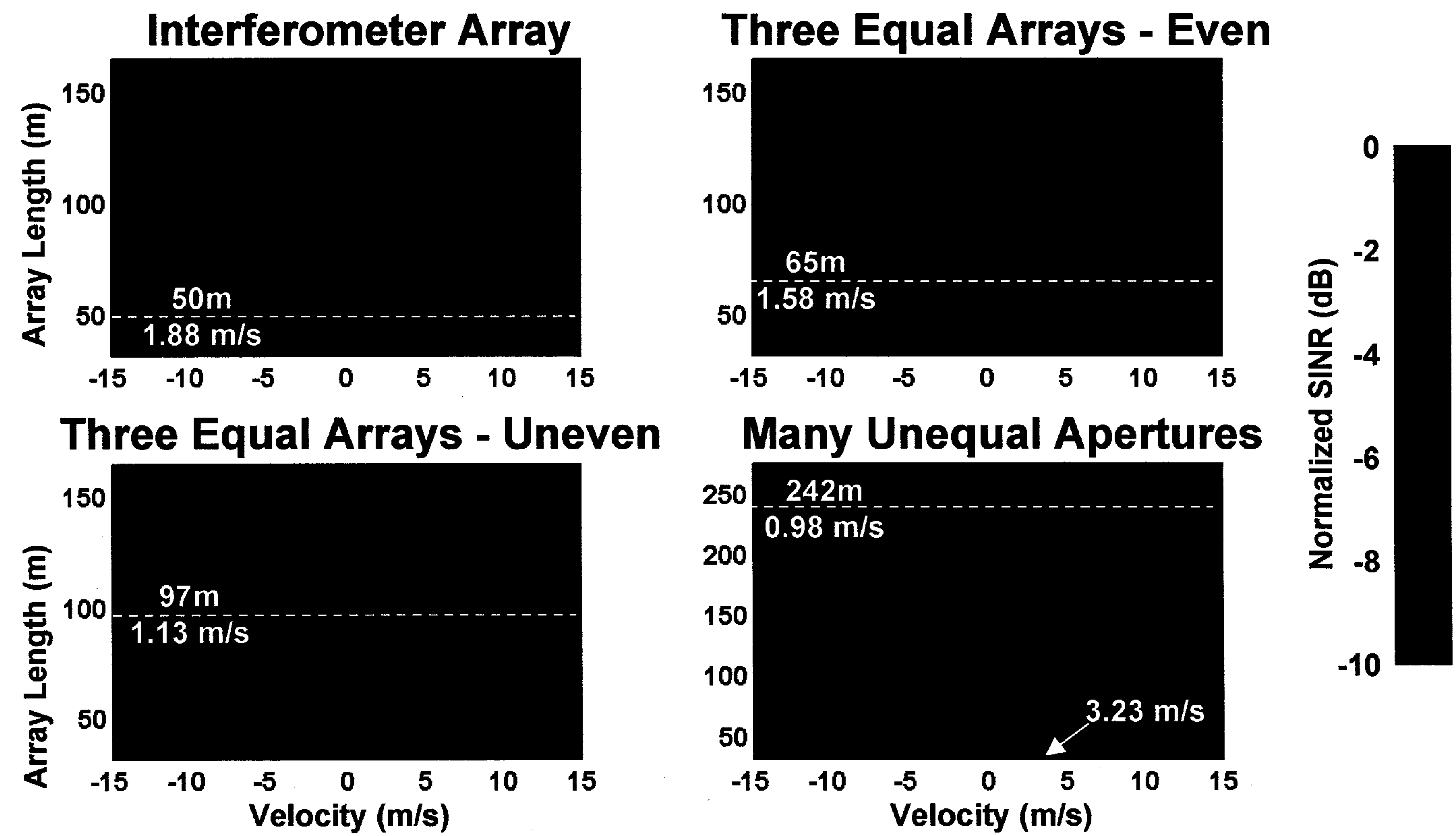
* Issues being addressed by Aerospace Corporation

0° Rotation Scenario



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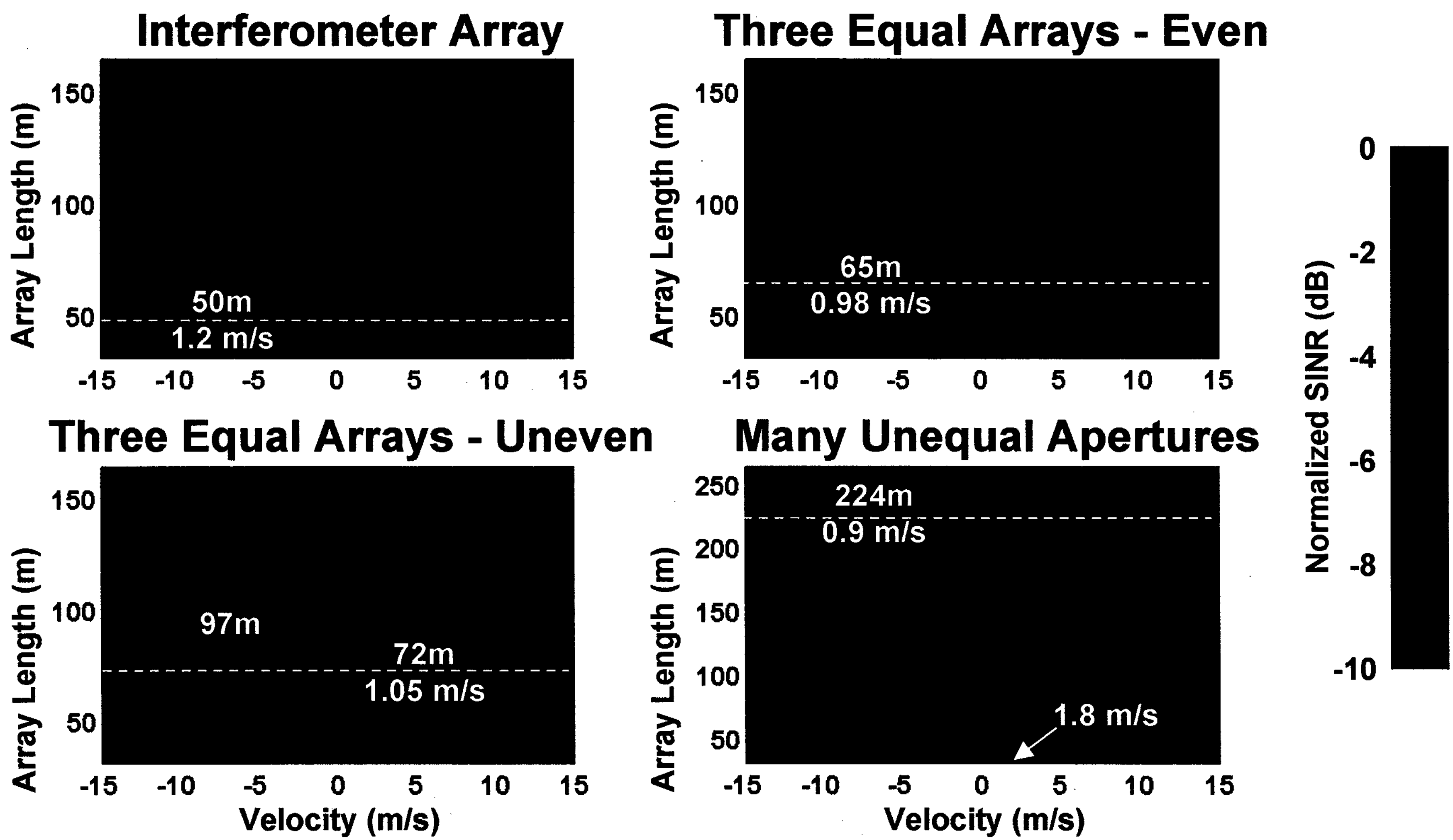
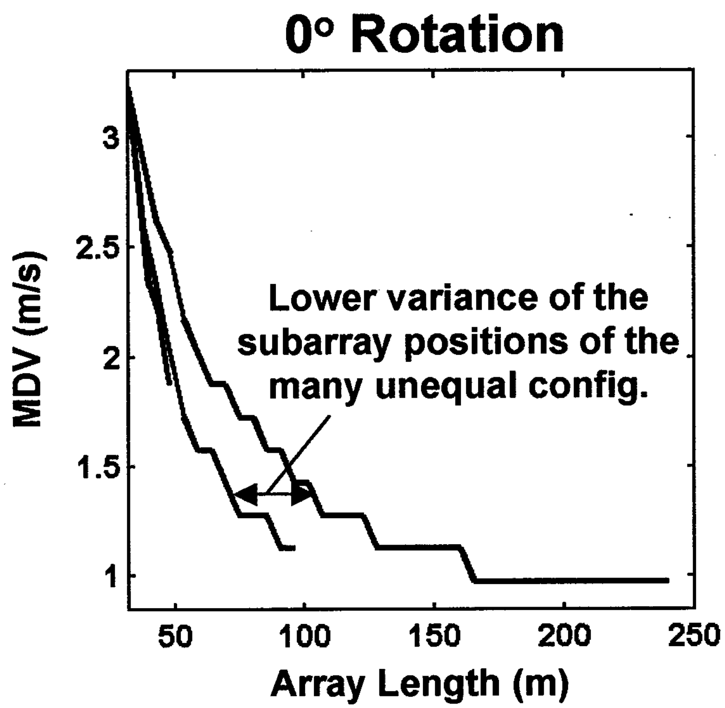
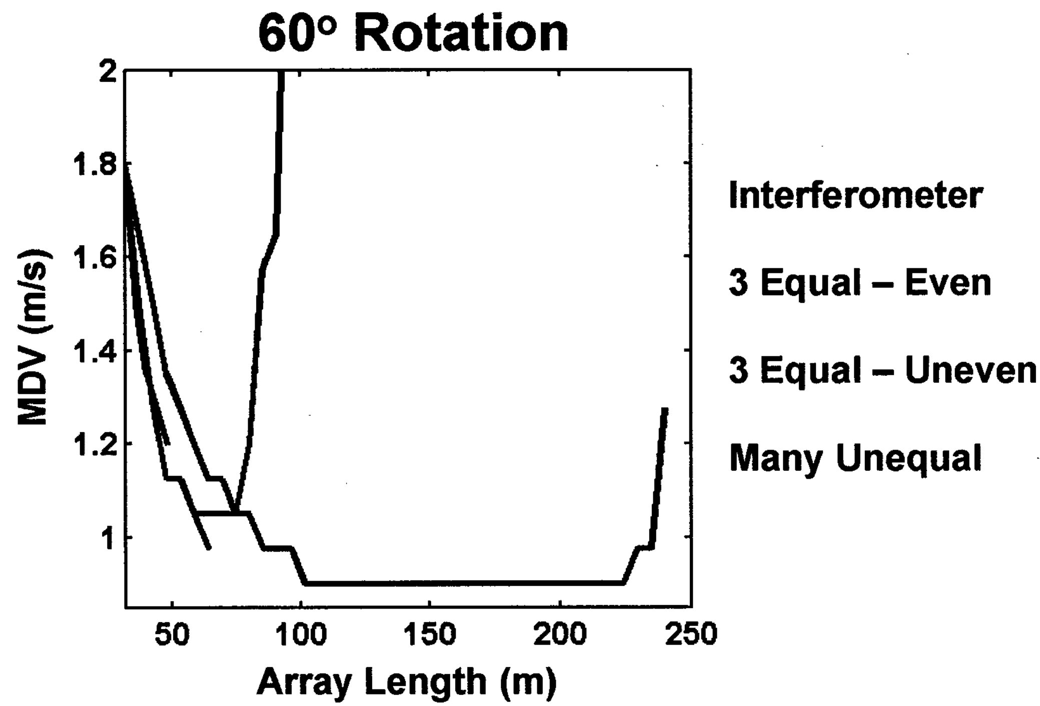
60° Rotation Scenario



-3 dB MDV vs. Array Length





- **Many unequal subarrays configuration needs a larger baseline to obtain the same performance as the other configurations, but ultimately provides the best MDV**
  - 165m aperture optimizes MDV for 2500 km range
  - Longer apertures improve angle metrics

Summary

- Sparse arrays potentially improve the minimum detectable performance of space-based radars
  - Approach the MDV performance of a large filled aperture much with lower size, weight and cost

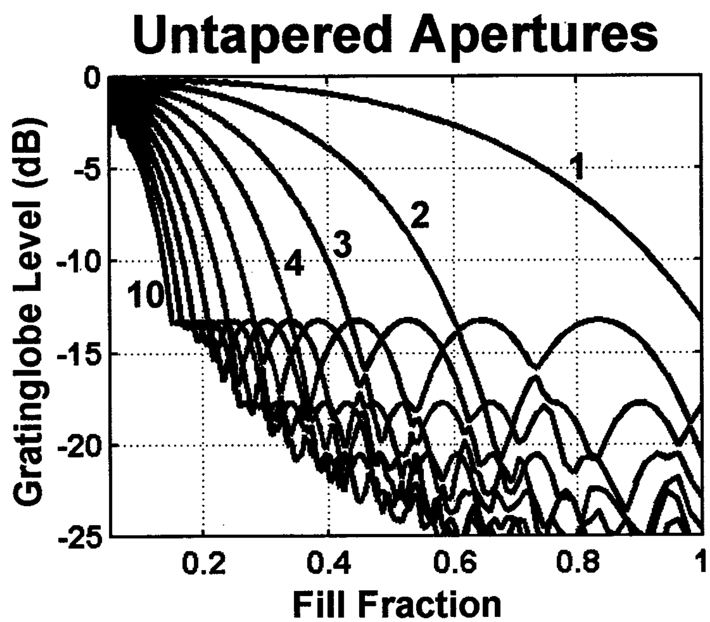
- Sparse arrays and sparse (pulse-Doppler) waveforms do not mix well
  - Sparse arrays perform well with Doppler unambiguous waveforms
  - Sparse waveforms (pulse-Doppler) perform well with filled arrays

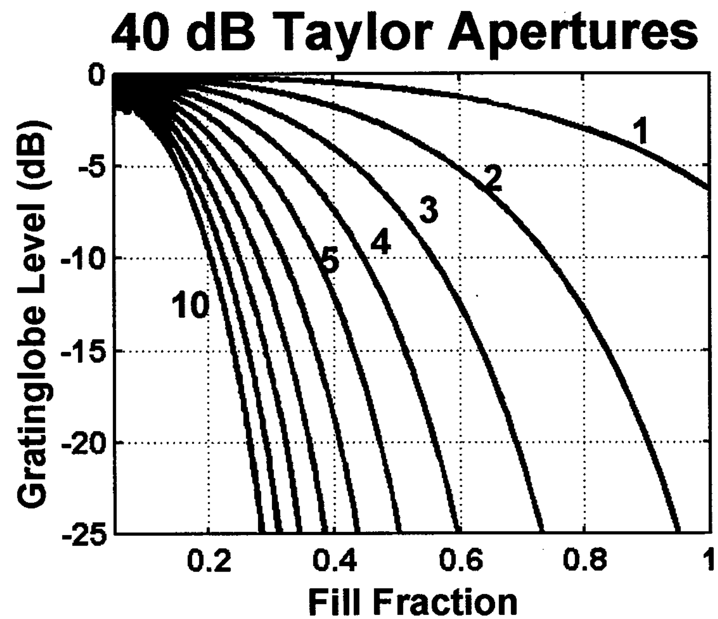
- Long single-pulse waveforms provide range and Doppler unambiguous operation and are compatible with current STAP algorithms

- Sparse arrays with many unevenly sized unevenly spaced subarrays provide the best GMTI performance

Backup Viewgraphs

Interferometer Array Grating Lobes

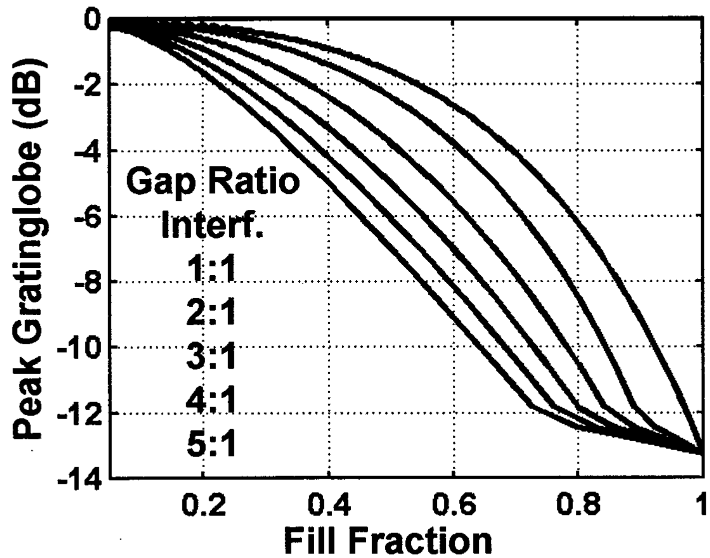


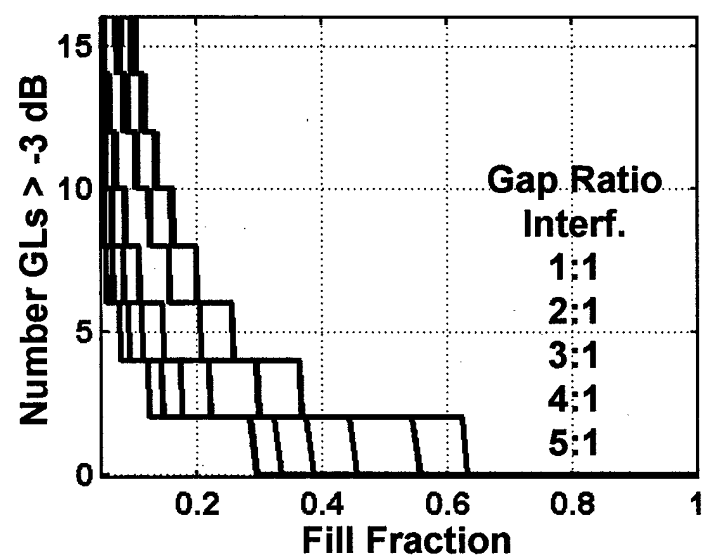


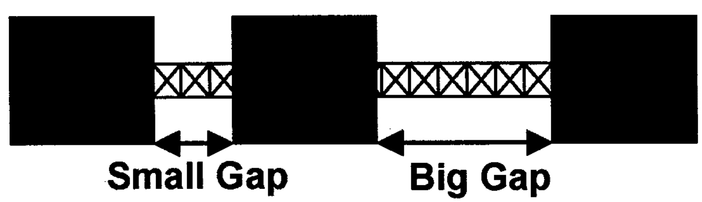
$$\text{Fill Fraction} = \frac{\text{Filled Aperture}}{\text{Total Aperture}}$$

- **Grating lobes quickly appear for interferometer array**
- **~$^{2}/_{3}$ fill fraction -3 dB grating lobes untapered apertures**

Grating Lobe Distributions
3 Equal Arrays



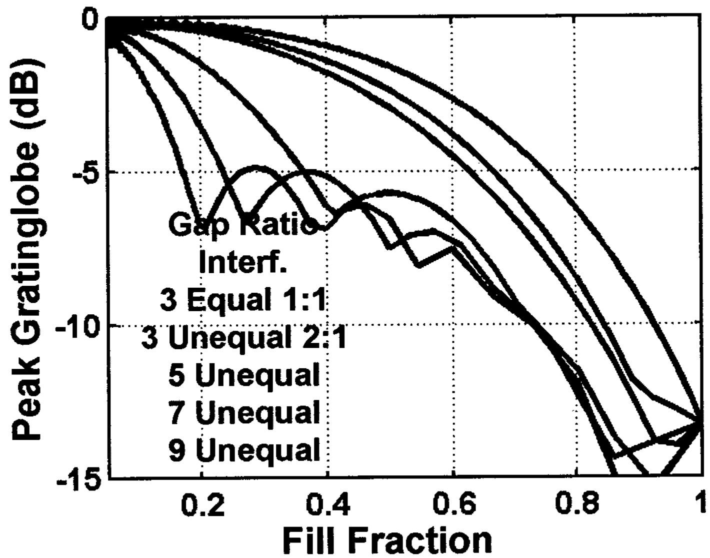


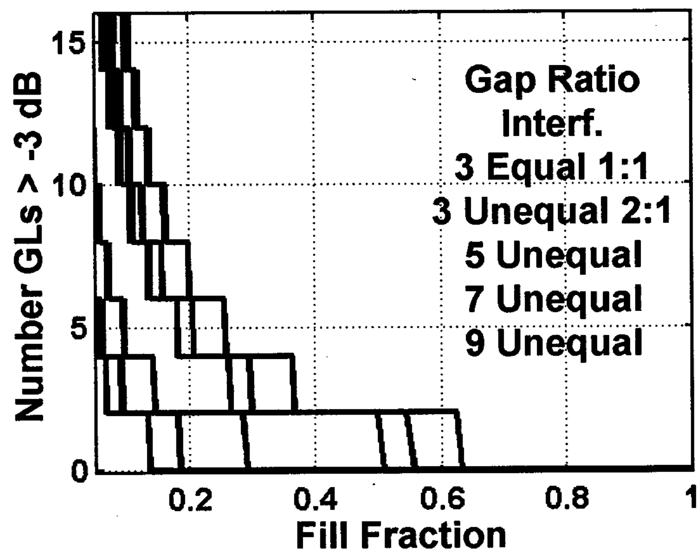


Gap Ratio = Big Gap : Small Gap

- **Lower grating lobes than interferometer**
- **Higher gap ratios lead to lower grating lobes**
  - **Also poorer MDV performance**

Grating Lobe Distributions
Unequal Arrays





50% filled aperture in center subarray

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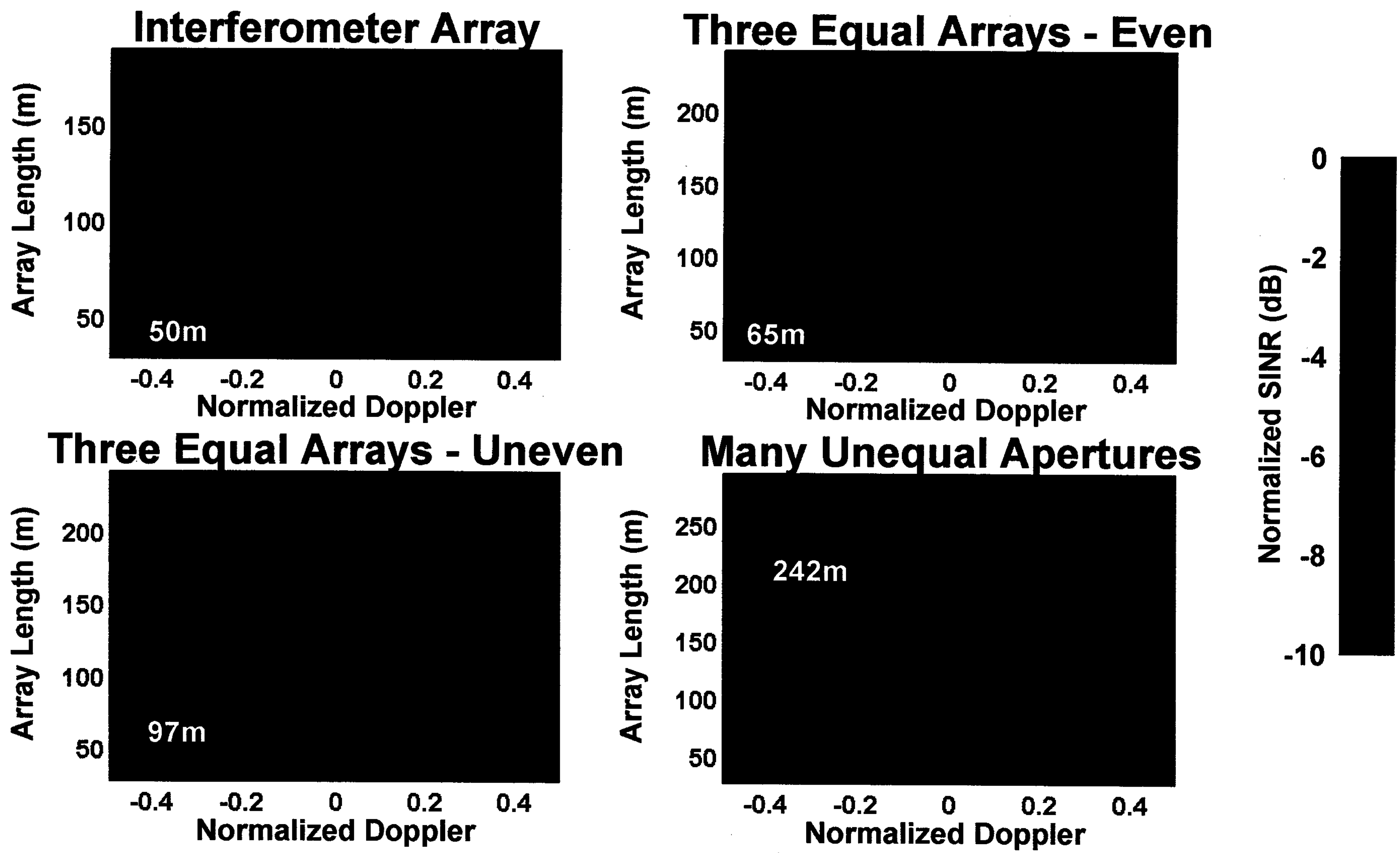
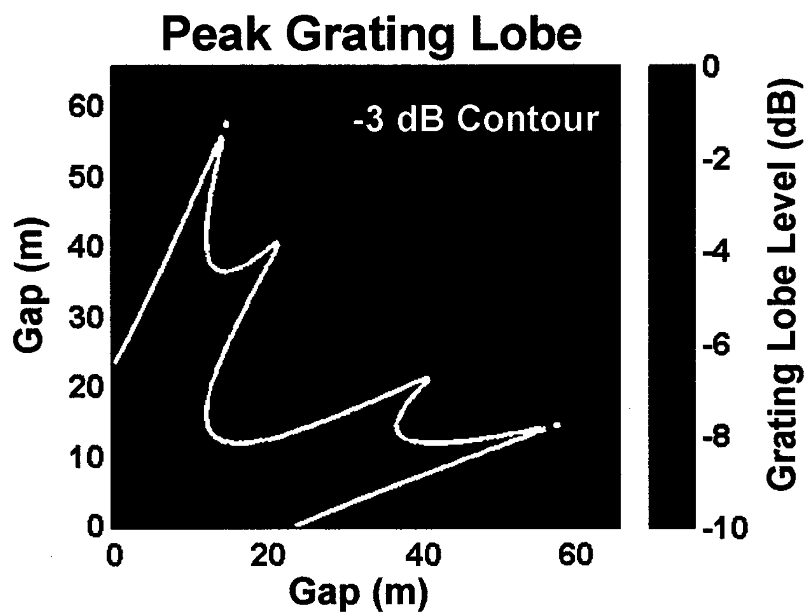
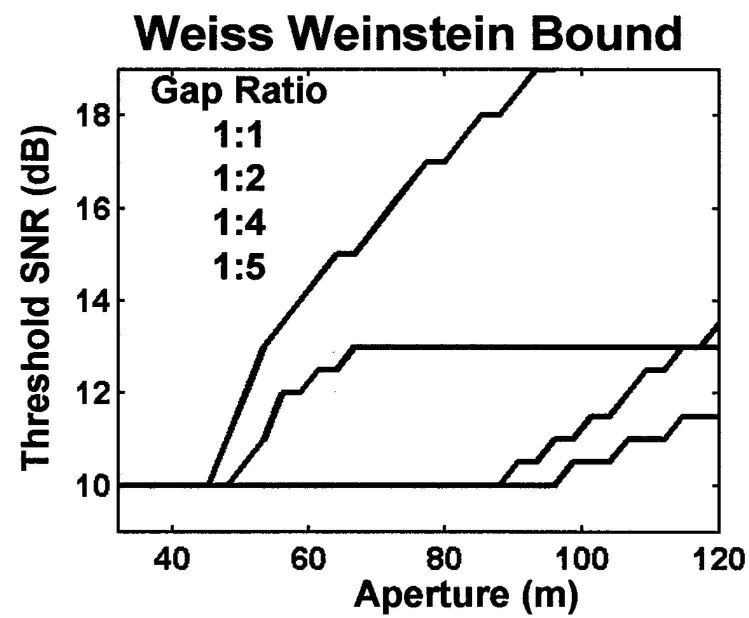
0° Rotation Scenario



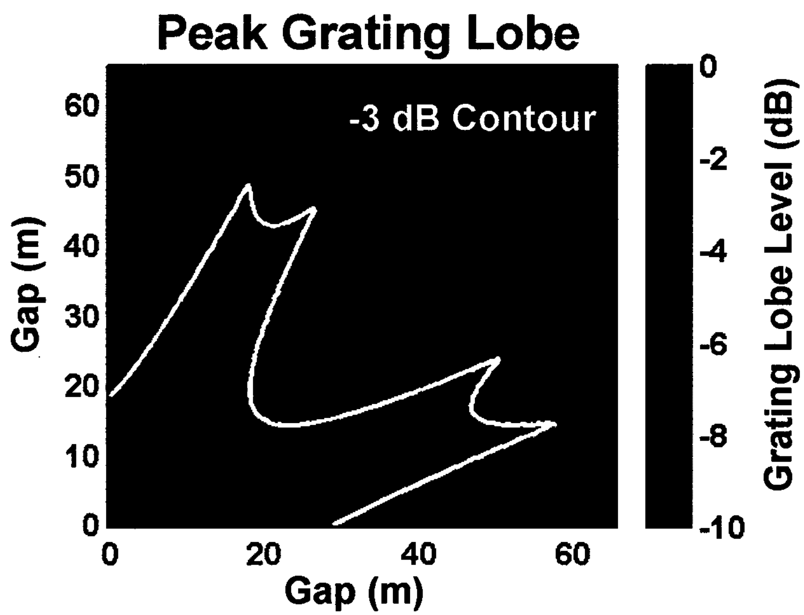
Three Equal Apertures Target Location

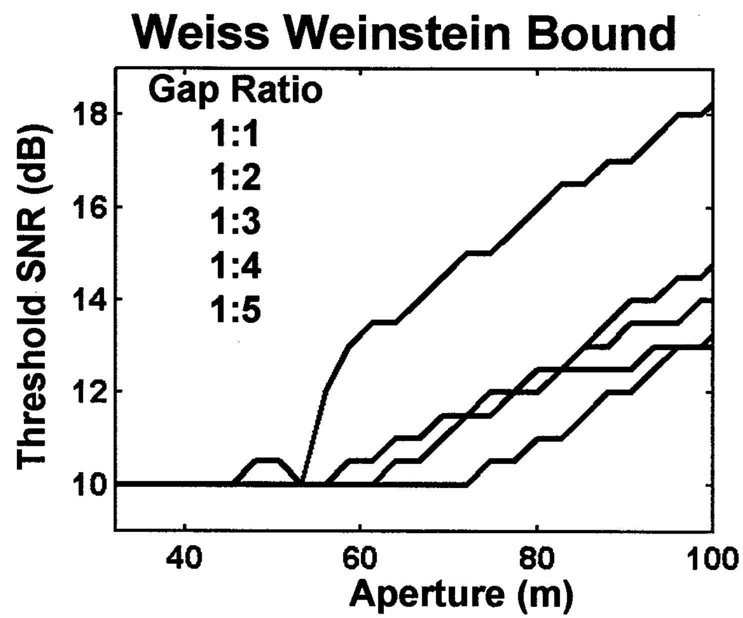




- 96 m aperture largest possible without increasing the threshold SNR
  – Provides 89 m rms error at 6° grazing
  – 82 m gives 107 m rms error

Three Unequal Apertures Target Location



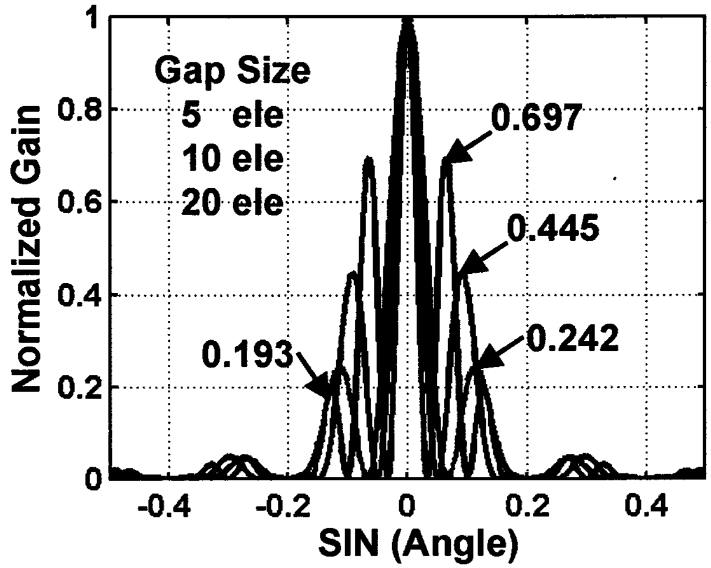


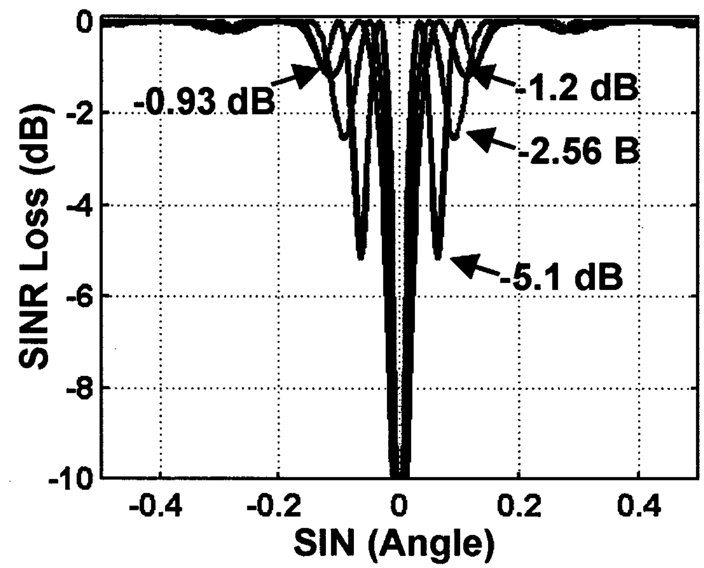
- 72 m aperture largest possible without increasing the threshold SNR
- 72m aperture Provides 119m rms error at 6° grazing

SINR Loss Due To Grating Lobe

(Spatial Only Example)

20 Element Array Example





- **Under the high INR assumption:**

$$\text{SINR Loss} \approx \boldsymbol{v}^H \boldsymbol{v} - \left| \boldsymbol{v}^H \mathbf{e} \right|^2 = 1 - \frac{\text{Grating Lobe Gain}}{\text{Mainbeam Gain}}$$

- **i.e., for 3 dB loss grating lobe gain (sum grating lobes for pulse-Doppler ?) must be 3 dB less than main lobe gain**